8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions in 2004, accounting for 25 percent of total U.S. CH_4 emissions.[1] Additionally, wastewater treatment accounts for 7 percent of U.S. CH_4 emissions. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas and indirect greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

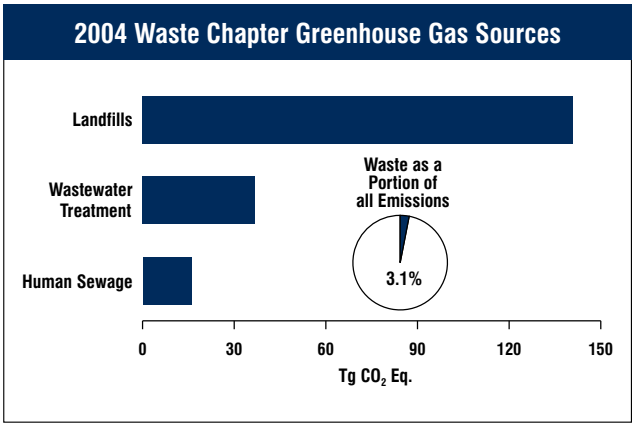
Overall, in 2004, waste activities generated emissions of 193.8 Tg CO_2 Eq., or 3 percent of total U.S. greenhouse gas emissions.

8.1. Landfills (IPCC Source Category 6A1)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2004, landfill CH_4 emissions were approximately 140.9 Tg CO_2 Eq. (6,709 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 (BioCycle 2004).

After being placed in a landfill, waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2]

Figure 8-1



[1] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of non-methane volatile organic compounds (NMVOCs).

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**197.1**	**176.9**	**175.3**	**173.3**	**170.8**	**175.6**	**179.0**	**177.8**
Landfills	172.3	144.4	141.6	139.0	136.2	139.8	142.4	140.9
Wastewater Treatment	24.8	32.6	33.6	34.3	34.7	35.8	36.6	36.9
N_2O	**12.9**	**14.9**	**15.4**	**15.5**	**15.6**	**15.6**	**15.8**	**16.0**
Human Sewage	12.9	14.9	15.4	15.5	15.6	15.6	15.8	16.0
Total	**210.0**	**191.8**	**190.7**	**188.8**	**186.4**	**191.3**	**194.8**	**193.8**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**9,385**	**8,425**	**8,346**	**8,254**	**8,135**	**8,364**	**8,524**	**8,467**
Landfills	8,206	6,874	6,743	6,619	6,484	6,659	6,782	6,709
Wastewater Treatment	1,180	1,550	1,602	1,635	1,651	1,705	1,742	1,758
N_2O	**42**	**48**	**50**	**50**	**50**	**50**	**51**	**52**
Human Sewage	42	48	50	50	50	50	51	52
NMVOCs	**673**	**161**	**140**	**119**	**122**	**133**	**134**	**134**
CO	**1**	**5**	**13**	**8**	**8**	**8**	**8**	**8**
NO_x	**+**	**3**	**3**	**2**	**2**	**2**	**2**	**2**

Note: Totals may not sum due to independent rounding.

Significant CH_4 production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years.

From 1990 to 2004, net CH_4 emissions from landfills decreased by approximately 18 percent (see Table 8-3 and Table 8-4), with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

CH_4 emissions from landfills are a function of several factors, including: (1) the total amount of municipal solid waste in landfills, which is related to total municipal solid waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in landfills increased from about 209 Tg in 1990 to 279 Tg in 2004, an increase of 33 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from landfills increased as well. In 1990, for example, approximately 930 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2004, the estimated quantity of CH_4 recovered and combusted increased to 5,343 Gg.

Over the next several years, the total amount of municipal solid waste generated is expected to increase as the U.S. population continues to grow. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to increase primarily as a result of 1996 federal regulations that require large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005), and the Landfill Methane Outreach Program (LMOP), an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Methodology

CH_4 emissions from landfills were estimated to equal the CH_4 produced from municipal solid waste landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
MSW Landfills	197.2	219.1	222.3	226.5	231.9	238.6	245.0	251.2
Industrial Landfills	13.8	15.3	15.6	15.9	16.2	16.7	17.2	17.6
Recovered								
Gas-to-Energy	(14.0)	(41.6)	(47.0)	(50.8)	(56.2)	(56.3)	(57.8)	(59.7)
Flared	(5.5)	(32.4)	(33.5)	(37.1)	(40.7)	(43.7)	(46.2)	(52.5)
Oxidized[a]	(19.1)	(16.0)	(15.7)	(15.4)	(15.1)	(15.5)	(15.8)	(15.7)
Total	**172.3**	**144.4**	**141.6**	**139.0**	**136.2**	**139.8**	**142.4**	**140.9**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
MSW Landfills	9,391	10,435	10,588	10,785	11,045	11,364	11,669	11,960
Industrial Landfills	657	730	741	755	773	795	817	837
Recovered								
Gas-to-Energy	(667)	(1,982)	(2,239)	(2,419)	(2,676)	(2,679)	(2,751)	(2,841)
Flared	(263)	(1,545)	(1,597)	(1,767)	(1,938)	(2,082)	(2,199)	(2,502)
Oxidized[a]	(912)	(764)	(749)	(735)	(720)	(740)	(754)	(745)
Total	**8,206**	**6,874**	**6,743**	**6,619**	**6,484**	**6,659**	**6,782**	**6,709**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere:

$$CH_{4,\text{ Solid Waste}} = [(CH_{4,MSW} - R) + CH_{4,ind}] - Ox$$

where,

$CH_{4,\text{ Solid Waste}}$ = CH_4 emissions from solid waste

$CH_{4,\text{ MSW}}$ = CH_4 generation from municipal solid waste landfills,

R = CH_4 recovered and combusted,

$CH_{4,\text{ ind}}$ = CH_4 generation from industrial landfills, and

Ox = CH_4 oxidized from MSW and industrial landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from municipal solid waste landfills is based on the first order decay model described in the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance* (IPCC 2000) and in a background paper prepared by Jensen and Pipatti (2002). Values for the CH_4 generation potential (L_0) and rate constant (k) were obtained from an analysis of CH_4 recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges, and historical census data were used to account for the shift in population to more arid areas over time. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 1989 through 2004 were obtained from *BioCycle* (2004). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2005) and national per capita solid waste generation from *BioCycle* (2004). Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's

Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by EPA's Landfill Methane Outreach Program (LMOP) (EPA 2005a), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2005). The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double-counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2004 was estimated. This quantity likely underestimates flaring because these databases do not have information on all flares in operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for 359 landfills with LFGTE projects. If a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (Mancinelli and McKay 1985; Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every landfill for each year of its operation. The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4 as determined from several studies of CH_4 recovery at landfills are representative of U.S. landfills. Also, the approach used to estimate the contribution of industrial non-hazardous wastes to total CH_4 generation introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation by cover soils.

The N_2O emissions from the application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. The total nitrogen (N) in sewage sludge increased from 189 to 261 Gg total N between 1990 and 2004, however; the quantity of sewage sludge applied to landfills decreased from 28 to 10 percent from 1990 to 2004.[3]

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2004 were estimated to be between 90.2 and 163.4 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of 36

[3] The methodology for estimating the quantity of N in sewage sludge disposed via incineration, land application, surface disposal, landfill, ocean dumping, and other is described in Annex 3.11 Methodology for Estimating N_2O Emissions From Agricultural Soil Management.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH_4	140.9	90.2	163.4	-36%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

percent below to 16 percent above the 2004 emission estimate of 140.9 Tg CO_2 Eq.

Recalculations Discussion

The primary recalculation was that associated with updating the EIA, LMOP, and flare vendor databases. The estimates of gas recovery at LFGTE projects decreased by 6.6 percent for the 2003 estimate, and most of this change is due to updating the EIA database. The EIA database for 2003 did not become available until late in 2004; consequently, the gas recovery rate for 2003 was estimated from the 2002 data. The 2004 update showed that LFGTE projects in the EIA 2002 database reported less gas recovery in 2003 than 2002, which decreased the estimate of CH_4 recovery. Another change affecting estimates of CH_4 recovery was due to additional projects reported in the EIA update that were previously included in the LMOP database. The recovery rates for these projects were changed to reflect the EIA estimate rather than the estimate of the LMOP database. A preference is given to the EIA database because those estimates are based on measured gas recovery rates, and they reflect changes in the recovery rate over time. Other changes affecting (decreasing) recovery rates over the time series resulted from identifying a few landfill projects that were inadvertently included in more than one of the three databases used to estimate gas recovery. There were also changes due to correcting and updating the LMOP database with changes in operational status and project start date. Overall, these changes resulted in an average annual decrease of 2.8 percent over the time series in CH_4 recovered by gas-to-energy projects.

Similar updates were made to the flare database and flares in the EIA database. The flare changes resulted in an average annual decrease of 8.4 percent in reductions due to flaring over the 1990 to 2003 time series. The primary factor causing this decrease was an adjustment made to the estimates for flaring when the flare vendor supplied information on the flare's maximum capacity. An analysis of flare capacity versus measured CH_4 flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the analysis was revised to estimate actual flow as 50 percent of capacity. Other factors contributing to the decrease were the update of the recovery by flares in the EIA database and removing flares inadvertently included in the flare database because they were reported in the EIA database. Average annual CH_4 emissions over the time series increased by 4 percent because of the decrease in estimates of CH_4 recovered for gas-to-energy projects and flaring.

The recovery of CH_4 for flaring increased by 14 percent from 2003 to 2004 (from 2,199 Gg to 2,502 Gg). This increase was due to 41 additional flares identified by flare vendors as becoming operational in 2004 and an additional 9 landfills with flares added to the EIA database. CH_4 recovery by LFGTE projects increased by 3 percent from 2003 to 2004 (from 2,751 Gg to 2,841 Gg). This increase was due to 22 new projects in the LMOP database becoming operational in 2004 and the addition of 4 new projects to the EIA database.

Planned Improvements

For future inventories, emerging guidance will be incorporated to help provide more accurate estimates of CH_4 generation by using the first order decay model and incorporating a delay time for CH_4 generation. The equation presented by Jensen and Pipatti (2002) and the 1996 IPCC guidance approximates the CH_4 generation rate using an estimate of the instantaneous rate at a point in time. This approximation simplifies estimating CH_4 generation using nationwide totals for waste disposal for each year. The revised guidance will improve the CH_4 generation estimate and incorporate a time lag to reflect the delay in CH_4

Box 8-1: Biogenic Emissions and Sinks of Carbon

CO_2 emissions from the combustion or decomposition of biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. However, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products, yard trimmings, and food scraps resulted in net long-term storage of 9.3 Tg CO_2 Eq. in 2004, as described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003).

generation from the time the waste is disposed. The new guidance will result in a decrease of about 2 percent in the CH_4 generation rates presented here.

Additional efforts will be made to improve the estimates of CH_4 generation at industrial landfills and estimates of oxidation, especially for landfills with gas recovery systems. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares. The parameters for the first order decay model will be re-evaluated as more data become available.

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater from domestic (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems (EPA 1996). Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), governs the CH_4 producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater.

In 2004, CH_4 emissions from domestic wastewater treatment were estimated to be 20.0 Tg CO_2 Eq. (953 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Also, the per capita organic wastewater loading has increased. In 2004, CH_4 emissions from industrial wastewater treatment were estimated to be 16.9 Tg CO_2 Eq. (805 Gg). Industrial emission sources include wastewater from the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.[4] Table 8-6 and Table 8-7 provide emission estimates from domestic and industrial wastewater treatment.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology:

$$CH_{4\ (\text{domestic wastewater})} = US_{POP} \times BOD_5 \times 365 \times 16.25\ \% \times EF$$

[4] Emissions associated with refinery wastewater are estimated in Annex 2.3 Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles, however emissions from these sectors are considered to be insignificant.

Table 8-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
Domestic	11.4	16.4	17.1	17.8	18.5	19.1	19.8	20.0
Industrial*	13.4	16.1	16.5	16.5	16.2	16.7	16.7	16.9
Total	**24.8**	**32.6**	**33.6**	**34.3**	**34.7**	**35.8**	**36.6**	**36.9**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.
Note: Totals may not sum due to independent rounding.

Table 8-7: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1998	1999	2000	2001	2002	2003	2004
Domestic	543	783	815	848	880	912	944	953
Industrial*	637	767	787	788	771	794	797	805
Total	**1,180**	**1,550**	**1,602**	**1,635**	**1,651**	**1,705**	**1,742**	**1,758**

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industries.
Note: Totals may not sum due to independent rounding.

where,

CH_4 = Total CH_4 emissions from domestic wastewater (kg/year)

US_{POP} = U.S. population

BOD_5 = organic loading in wastewater (kg BOD_5/person.day)[5]

365 = days per year

16.25% = Percent of wastewater BOD_5 that is anaerobically digested

EF = Emission factor (0.6 kg CH_4/kg BOD_5)

National population data for 1990 to 2004, used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2005). For BOD_5 for domestic wastewater, two data points were available, for 1991 and 2003 (Metcalf & Eddy 1990; Metcalf & Eddy 2003). The BOD loadings for intervening years were obtained by linear interpolation. Table 8-8 presents population and domestic wastewater BOD_5 produced. The emission factor (0.6 kg CH_4/kg BOD_5) was taken from IPCC *Good Practice Guidance* (IPCC 2000). The percent of wastewater BOD_5 that was anaerobically digested was assumed to be 16.25 percent (ARCADIS 2001). This value also accounts for U.S. septic systems and is based on expert judgment and on septic system usage data from EPA (1996).

CH_4 emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2000). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified. High volumes of wastewater generated and a high organic wastewater load were the main criteria. The top three industries that meet these criteria are pulp and paper manufacturing; meat and poultry packing; and vegetables, fruits, and juices processing. Table 8-9 presents the U.S. production of pulp and paper; meat and poultry; and vegetables, fruits, and juices.

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	5,566
1998	280	8,032
1999	283	8,363
2000	286	8,695
2001	289	9,021
2002	292	9,351
2003	295	9,685
2004	297	9,774

Source: U.S. Census Bureau (2005); Metcalf & Eddy 1990; Metcalf & Eddy 2003.

[5] BOD_5 is the 5-day biochemical oxygen demand measurement (Metcalf and Eddy 2003).

CH_4 emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD or BOD) in the outflow, the percentage of organic loading assumed to degrade anaerobically, and the emission factor. For pulp and paper as well as meat and poultry wastewater, BOD was used. In developing estimates for the vegetables, fruits, and juices category, COD was used instead of BOD, because no accurate BOD numbers were available. The emission factor used for pulp and paper as well as meat and poultry wastewater is 0.6 kg CH_4/kg BOD_5, whereas the emission factor for vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000). The methodological equation is:

$$CH_{4\ (industrial\ wastewater)} = P \times W \times (COD\ or\ BOD) \times MCF \times EF$$

where,

$CH_{4\ (industrial\ wastewater)}$ = Total CH_4 emissions from industrial wastewater (kg/year)

P = Industry output (metric tons/year)

W = Wastewater generated (m^3/metric ton of product)

COD or BOD = Organics loading in wastewater (kg /m^3)

MCF = CH_4 correction factor, indicating the extent to which the organic COD or BOD degrades anaerobically

EF = Emission factor (0.6 kg CH_4/kg BOD_5 for meat and poultry and pulp and paper; 0.25 kg CH_4/kg COD for vegetables, fruits and juices)

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur and, consequently, the primary lagoons are assumed to be 1.4 percent anaerobic (expert judgment). Approximately 42 percent of the BOD passes on to secondary treatment, which is less likely to be aerated (EPA 1993). Twenty-five percent of the BOD in secondary treatment lagoons was assumed to degrade anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Consequently, the overall percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent (i.e., 58% × 1.4% + 42% × 90% × 25%). A time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999).

Table 8-9: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Tg)

Year	Pulp and Paper	Meat (carcass weight)	Poultry (carcass weight)	Vegetables, Fruits and Juices
1990	128.9	17.6	10.6	29.8
1995	140.9	19.8	13.8	36.8
1996	140.3	19.8	14.5	36.4
1997	145.6	19.7	15.0	37.7
1998	144.0	20.5	15.1	36.5
1999	145.1	21.0	16.0	37.4
2000	142.8	21.0	16.4	38.9
2001	134.3	20.8	16.8	35.0
2002	137.5	21.5	17.3	36.5
2003	140.0	21.2	17.5	34.1
2004	140.0	21.5	17.7	36.6

Table 8-10: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	CH_4	36.9	24.9	51.2	-33%	+39%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps and dissolved air flotation. Production data, in carcass weight for the meat and poultry industry, were obtained from the U.S. Census (2004). EPA (2002) provided estimates for wastewater flows into anaerobic lagoons: 7.9 and 16.6 m^3/metric ton for meat and poultry production, respectively. The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. Ninety percent of organic BOD is believed to degrade anaerobically in the lagoon (EPA 1997b).

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 5 percent of these wastewater organics are assumed to degrade anaerobically. The USDA National Agricultural Statistics Service (USDA 2004) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m^3/metric ton was used. For the organics loading, a COD value of 5 g/liter was used (EPA 1997b).

Uncertainty

The overall uncertainty associated with the 2004 CH_4 emissions estimate from wastewater treatment was calculated using the IPCC *Good Practice Guidance* Tier 2 methodology. Uncertainty associated with the parameters used to estimate CH_4 emissions included that of numerous input variables used to model emissions from domestic wastewater, and wastewater from the pulp and paper industry, meat and poultry processing, as well as from fruits, vegetables and juices processing.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-10. CH_4 emissions from wastewater treatment were estimated to be between 24.9 and 51.2 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 33 percent below to 39 percent above the 2004 emissions estimate of 36.9 Tg CO_2 Eq.

Recalculations Discussion

The 2004 estimates did not include any methodological changes or refinements. However, the time series for domestic wastewater changed because population estimates for the United States and U.S. territories changed slightly. This change resulted in a less than one percent decrease in emission estimates over the time series.

Planned Improvements Discussion

The methodology to estimate emissions from domestic wastewater uses a factor of 16.25 percent for the overall quantity of organics (BOD) in wastewater that is anaerobically digested. This factor is based on the percentage of the population that uses septic systems and on the amount of BOD that degrades anaerobically in septic systems and in centralized treatment plants. Information may be available that will allow for refinement of this factor. Another area for improvement is characterization of pulp and paper wastewater treatment (organics loading, wastewater generation and anaerobic degradation percentage).

8.3. Human Sewage (Domestic Wastewater) (IPCC Source Category 6B)

Domestic human sewage is usually mixed with other household wastewater, which includes effluent from shower drains, sink drains, washing machines, etc., and is either discharged directly, or transported to an on-site or decentralized wastewater treatment system, or to a centralized wastewater treatment system. Decentralized wastewater treatment systems are septic systems and package plants. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized wastewater treatment systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent is discharged to a receiving water environment (e.g., river, lake, estuary, etc.), or applied to soils, or disposed of below the surface.

N_2O may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3^-) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes, but is more often associated with denitrification.

The United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes; and emissions from effluent that has been discharged into aquatic environments. The 2004 emissions of N_2O from wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 15.8 Tg CO_2 Eq. (51 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 16.0 Tg CO_2 Eq. (52 Gg) (see Table 8-11). Emissions from wastewater treatment processes have gradually increased as a result of increasing U.S. population and protein consumption.

Table 8-11: N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	12.9	42
1998	14.9	48
1999	15.4	50
2000	15.5	50
2001	15.6	50
2002	15.6	50
2003	15.8	51
2004	16.0	52

Methodology

The IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) assumes that nitrogen disposal, and thus N_2O emissions associated with land disposal, subsurface disposal, and domestic wastewater treatment are negligible and all nitrogen is discharged directly into aquatic environments. For the United States, N_2O emissions from domestic wastewater (human sewage) were estimated using the IPCC methodology with three modifications:

- In the United States, a certain amount of nitrogen is removed with sewage sludge, which is applied to land, incinerated or landfilled (N_{sludge}). The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.[6]
- The IPCC methodology uses annual, per capita protein consumption (kg protein/(person-year)). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. A factor of 1.4 is introduced to account for non-consumption nitrogen.[7] Furthermore, a

[6] The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11 Methodology for Estimating N_2O Emissions From Agricultural Soil Management.

[7] Metcalf & Eddy (1991) provides an indication of the nitrogen concentration of 40 mg Total Kjeldahl Nitrogen (TKN)/liter for average wastewater from residences, which includes bathwater, laundry, and the use of garbage disposals. According to the Needs Survey (1996), the total volume of wastewater generated in the United States in 1996 was 32,175 million gallons per day (MGD), serving 189,710,899 people (72 percent of population, not including the septic system users). In 1996, the per capita TKN loading was: 40 [mg/l] × 32,175 × 10^6 [gal/day] × 3.8 [l/gal] × 365 days/yr × 1/(189.7 × 10^6) × 10^{-6} = 9.4 [kg TKN/yr.person]. Average protein intake in 1996 was 41 kg protein /(person-year) (6.6 kg N/(person-year)), leading to a factor of 1.4 (9.4/6.6).

significant quantity of industrial wastewater (nitrogen) is co-discharged with domestic wastewater. To account for this, a factor of 1.25 is introduced.[8] In summary, a factor of 1.75 (1.4 × 1.25) is used to account for the extra nitrogen discharge from kitchen, bath, and laundry wastes, as well as industrial wastewater that is co-discharged into sewers, based on Metcalf & Eddy (1991) and expert judgment.

- Process emissions from wastewater treatment plants are not accounted for in the current IPCC methodology. To estimate N_2O emissions from U.S. wastewater treatment plants, an overall emission factor (4 g N_2O/(person-year)) was introduced. This emission factor is based on a factor of 3.2 g N_2O/(person-year) (Czepiel et al. 1995) multiplied by the 1.25 factor mentioned above, which adjusts for co-discharged industrial nitrogen and is based on expert judgment. The nitrogen quantity associated with these emissions (N_{WWT}) is calculated by multiplying the N_2O emitted by (2 × 14)/44 and is subtracted from the total quantity of nitrogen that is ultimately disposed into the aquatic environment.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {}^{44}/_{28}\}$$

where,

$N_2O(s)$ = N_2O emissions from domestic wastewater ("human sewage") [kg/year]

US_{POP} = U.S. population

0.75 = Fraction of population using centralized wastewater treatment plants (as opposed to septic systems)

EF_1 = Emission factor (4 g N_2O/person-year) expressing emissions from the centralized wastewater treatment plants

Protein = Annual per capita protein consumption [kg N/(person-year)]

1.75 = Fraction of non-consumption protein in domestic wastewater

$Frac_{NP}$ = Fraction of nitrogen in protein (i.e., 0.16 kg N/kg protein)

N_{WWT} = Quantity of wastewater nitrogen removed by wastewater treatment processes $[(US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) \times {}^{28}/_{44}]$ ([kg N/year)

N_{sludge} = Quantity of sewage sludge N not entering aquatic environments (kg N/year)

EF_2 = Emission factor (kg N_2O-N/kg sewage-N produced)

$({}^{44}/_{28})$ = Molecular weight ratio of N_2O to N_2.

U.S. population data were taken from the U.S. Census Bureau International Database (2005) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is from the Needs Survey (EPA 1996). The emission factor (EF_1) to estimate emissions from wastewater treatment is based on Czepiel, et al. (1995). Data on annual per capita protein intake were provided by the United Nations Food and Agriculture Organization for the 1990 to 2002 time frame (FAO, 2002). Because data on protein intake were unavailable for 2003 and 2004, the value of per capita protein consumption was extrapolated from previous years.

Table 8-12: U.S. Population (Millions) and Average Protein Intake [kg/(person-year)]

Year	Population	Protein
1990	254	39.2
1998	280	41.2
1999	283	42.0
2000	286	41.9
2001	289	41.8
2002	292	41.6
2003	295	41.8
2004	297	42.0

Source: U.S. Census Bureau 2005, FAO 2002, and extrapolation from FAO 2002.

[8] The type, composition, and quantity of this co-discharged wastewater vary greatly between municipalities. Metcalf & Eddy (1991) provide an indicative nitrogen loading of 20 to 85 mg TKN/liter (average 55) for combined residential and industrial wastewater, while residential wastewater loading was roughly estimated at 40 mg TKN/liter (see previous footnote). Until better data become available, the amount of N in wastewater is increased by 10 mg/l to account for industrial co-discharge (factor of 1.25).

Table 8-12 presents the data for U.S. population and average protein intake. An emission factor to estimate emissions from effluent (EF_2) has not been specifically estimated for the United States, thus the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

The overall uncertainty associated with the 2004 N_2O emissions estimate from human sewage was calculated using the IPCC *Good Practice Guidance* Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of nitrogen in protein, non-consumption nitrogen factor, emission factors for individuals and per mass of wastewater, and for the percentage of total population using centralized wastewater treatment plants. The activity data inputs and their associated uncertainties and distributions are summarized in Table 8-13.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-14. N_2O emissions from human sewage were estimated to be between 4.1 and 30.3 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 75 percent below to 89 percent above the 2004 emissions estimate of 16.0 Tg CO_2 Eq.

Planned Improvements

The default emission factor for N_2O from wastewater effluent has a high uncertainty. Future research may identify new studies that include updated data. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Several parameters constituting this factor are based on references that have since been updated, including the Needs Survey (1996) and Metcalf & Eddy (1991). The uncertainty associated with this factor can likely be reduced by incorporating more recent data. Also, the fraction of the U.S. population using centralized wastewater treatment plants is currently set at 0.75. This fraction can likely be refined with recent data from the 2004 Needs Survey. The U.S. Environmental Protection Agency intends to conduct research to update the protein consumption data.

Table 8-13: Sources of Uncertainty in N_2O Emissions from Human Sewage

Variable	Value	Distribution Type	Uncertainty Range[a]		Reference
			Lower Bound	Upper Bound	
Sewage Sludge Disposal (10^6 metric tons total N)	0.26	Triangular	-39%	+39%	Expert Judgment
U.S. and Territories Total Population (million persons)	297	Normal	-5%	+5%	Expert Judgment
Protein (kg/(person-yr))	42	Normal	-5%	+5%	Expert Judgment
Fraction of Nitrogen in Protein (kg N/kg protein)	0.16	Normal	-2%	+2%	Expert Judgment
Fraction of Non-Consumption Protein in Domestic WW	1.75	Normal	-25%	+25%	Expert Judgment
EF_2 (kg N_2O-N/kg sewage-N produced)	0.01	Normal	-80%	+80%	IPCC Guidelines
Population Using Centralized Wastewater Treatment Plants (%)	75%	Normal	-25%	+25%	Expert Judgment
EF_1 (g N_2O/(person-year))	4.0	Normal	-50%	+50%	Expert Judgment

[a] Parameters presented represent upper and lower bounds as a percentage of the mean, based on a 95 percent confidence interval.

Table 8-14: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Human Sewage	N_2O	16.0	4.1	30.3	-75%	+89%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

The 2004 estimates did not include any methodological changes or refinements. However, the time series for domestic wastewater changed because the amount of nitrogen that is removed with the sewage sludge (i.e., N_{sludge}) was adjusted to include N from surface disposal, ocean dumping, and other disposals of N, in addition to sewage sludge that is incinerated, applied to land, or landfilled. This change resulted in less than a one percent decrease in emission estimates over the time series relative to the previous report.

8.4. Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2004 are provided in Table 8-15.

Methodology and Data Sources

These emission estimates were obtained from preliminary data (EPA 2005), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 8-15: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
NO_x	**+**	**3**	**3**	**2**	**2**	**2**	**2**	**2**
Landfills	+	2	3	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+	+
CO	**1**	**5**	**13**	**8**	**8**	**8**	**8**	**8**
Landfills	1	5	12	7	7	7	7	7
Wastewater Treatment	+	+	1	1	1	1	1	1
Miscellaneous[a]	+	+	+	+	+	+	+	+
NMVOCs	**673**	**161**	**140**	**119**	**122**	**133**	**134**	**134**
Landfills	58	33	27	23	23	25	25	25
Wastewater Treatment	57	63	59	51	53	58	58	58
Miscellaneous[a]	558	65	54	46	46	51	51	51

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg.

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